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This paper describes the technology behind the development of the USN APACS man-mounted cooling system, a key component of HAILSS. APACS represents a lightweight, man-mounted cooling system for aircrews requiring no airframe modifications. This system is suitable for all crew stations and can be used during preflight inspections or by nonflying personnel.

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Development of the U.S. Navy Advanced Personal Air Conditioning System (APACS)

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Introduction: Helicopter aircrews are exposed to a variety of stressors (e.g., heat, humidity, physical and cognitive workloads) and potential hazards (e.g., cold water ditching) while performing normal peacetime operations. Combat adds significantly to aircrew physical and psychological demands due to added risks (ballistic threats, exposure to chemical/ biological warfare (CBW) agents). Personal protective equipment assists aircrews in meeting these demands but also adds to thermal burdens by imposing additional bulk and thermal insulation on the individual. One possible consequence of these cumulative stresses is hyperthermia, a potentially dangerous condition which can severely degrade mission performance and, in extreme cases, cause fatalities.

Specific garments intended to provide protection against fire, chemical and biological warfare (CBW) threats or immersion hypothermia (in case of ditching) can retain large quantities of body heat due to their impermeable nature. Semi-permeable CBW protective garments such as the USN Mk1 (Mk1) using carbon-impregnated fabrics reduce this heat burden by allowing convective heat exchange to occur across the semi-permeable fabric. Unfortunately, certain types of CBW agents can exploit this permeability. Advanced concept CBW protective fabrics enhance agent protection but retain greater quantities of body heat. In addition, protection against other threats requires individuals to wear multiple garment layers which leads to additional heat retention. Body heat trapped within these encapsulating garments needs to be removed if the garment user is to adequately perform required tasks, especially when users are physically active. These cooling requirements may increase substantially in the future greater because advanced warfighting concepts envision routine use of CBW protection.

External energy sources (aircraft engine, avionics, solar radiation) can exacerbate the thermal burden on individuals. Cooling system capabilities must also account for these heat sources when CBW protection is used. Presently available man-mountable systems are inadequate to provide sufficient heat extraction for extended (> 1-2 hours) missions. Furthermore, reliability and field reparability are also issues for both current and proposed systems due to their complex design.

The Naval Air Warfare Center Aircraft Division, in collaboration with the SD&E (Germany) and Gentex Corp., is developing a man-mounted air conditioning system which will address cooling needs of helicopter aircrew as part of the Helicopter Aircrew Integrated Life Support System (HAILSS). The Advanced Personal Air Conditioning System (APACS) is designed to be efficient, lightweight, simple to maintain, and have low power requirements. Mobility is a critical issue when preflighting an aircraft or performing physical tasks in a helicopter rear cabin. Man-mounting and providing a self-contained power supply allows by all crewmembers to use APACS independent of aircraft systems.

Physiological Heat Loss: Heat exchange between the human body and its surroundings can be described by the mechanisms depicted in Figure 1. Latent heat loss (evaporation) is the most efficient physiological heat loss mechanism and accounts for the bulk of heat loss during exposure to significant heat stress. Liquid produced by sweat glands and water routinely diffusing across the skin absorb energy from the skin, change phase into a vapor, and release that energy (2.3 kJ/g) to the surrounding environment.

Sensible heat loss (convection, conduction, and radiation) also plays a significant role in the normal heat exchange between the body and its surroundings. Convection occurs when a temperature difference exists between a surface (skin) and a moving fluid (gas or liquid) directly above the surface. Conduction accounts for the heat transfer occurring when a temperature difference exists between materials in direct contact. The rate of both convective and conductive heat exchange is a function of the first order temperature difference ($T_{surface}$-$T_{surroundings}$). Radiant heat exchange occurs when a relatively warm surface can transmit energy to a cooler surface through a transparent medium and is a function of the fourth order temperature difference (T_{warm}^4-T_{cool}^4). Convection and radiation generally play the most significant sensible heat loss roles in clothing since clothing does not contact the skin over most of its surface.

The relative contribution of latent and sensible heat loss to overall physiological heat loss depends on the relative humidity of the surroundings. Latent heat loss effectiveness is inversely proportionate to ambient relative humidity (RH). Consequently, sensible heat exchange accounts for most heat loss at high ambient RH.

Heat Burden Due to Physical Work: Physical work generates heat in addition to any heat burden associated with the ambient environment. Perfoming aircraft-related physical tasks (walking, flying, cargo handling) require muscle movement. Energy generated by muscle movement is divided between performance of physical work and metabolic heat. A simplistic breakdown of heat production during work is shown in Table 1. Estimated heat production from flying can range from 8 kJ/min (routine flying) to 15 kJ/min (combat flying). Other aircraft-related tasks such as handling heavy cargo can produce upwards of 25 kJ/min. This heat must be extract from aircrew if heat-associated illness is to be avoided.

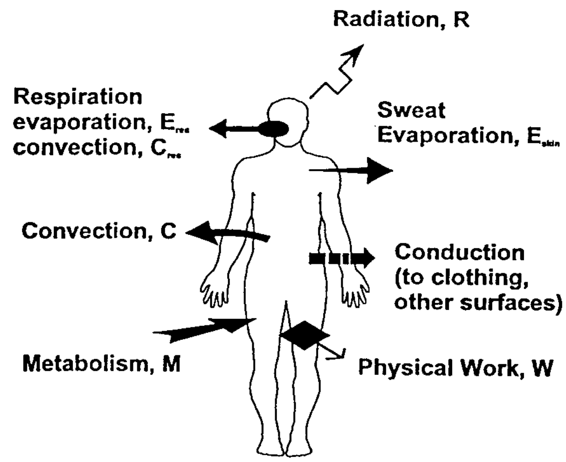

Figure 1. Physiological heat loss pathways.

Table 1. Metabolic heat generated by various work levels

Exertion level	Heat produced (kJ/min)
Light work	< 10
Moderate work	10 - 21
Heavy work	21 - 31
Very heavy work	31- 41

Heat Exchange Media: Most field-deployed cooling systems employ either air or liquid (water, freon) as the heat exchange medium. Table 2 compares how heat exchange occurs with each of these basic cooling systems while Table 3 compares the advantages and disadvantages of each system.

Table 2. Comparison of air- and liquid-based cooling system cooling processes.

Cooling Medium	Mechanism of action
Air	▪ Ventilation air cooled & dried ▪ Air blown through garment microenvironment ▪ Extracts heat via evaporation, convection ▪ Cools & dries microenvironment
Liquid	• Heat transfer fluid cooled • Liquid flows through tubing garment • Extracts heat via convection, conduction • Cools microenvironment

Table 3. Comparative advantages and disadvantages of air- and liquid-based cooling systems.

Cooling Medium	Advantages	Disadvantages
Air	▲ Employs natural sweat evaporation ▲ Enhances convective cooling ▲ Lightweight ▲ Low power consumption ▲ Uses existing hardware	▼ Difficult to cool inlet air ▼ Inlet air filtration (CBW) ▼ Blower design ▼ Depends on sweat output ▼ Difficult to control cooling rate
Liquid	▲ Sealed system ▲ High heat capacity medium ▲ Control of heat extraction rate ▲ Capable of dealing with high metabolic rates	▼ Clothing/vehicle redesign ▼ Weight ▼ Potential leakage ▼ Condensation ▼ Energy required

APACS Technology: The APACS system is based on zeolite, a class of porous spherical aluminosilicate minerals with a tremendous affinity for adsorbing water molecules. This has been utilized as the basis for development of a lightweight, man mountable air conditioning system with low power requirements. Figure 2 shows a schematic drawing of the underlying concept. Relatively warm ambient air passes over a heat exchanger containing liquid water and maintained at subatmospheric pressure. Air temperature drops as heat flows from the ventilation air through the heat exchanger shell and into the liquid water. Boiling occurs at less than room temperature because of the reduced pressure, extracting energy (heat of vaporization) from the heat exchanger surface, and producing water vapor that passes from the heat exchanger to the zeolite bed. This transfer of latent heat maintains low heat exchanger temperatures while the zeolite bed temperature rises due to the release of heat generated by adsorbtion.

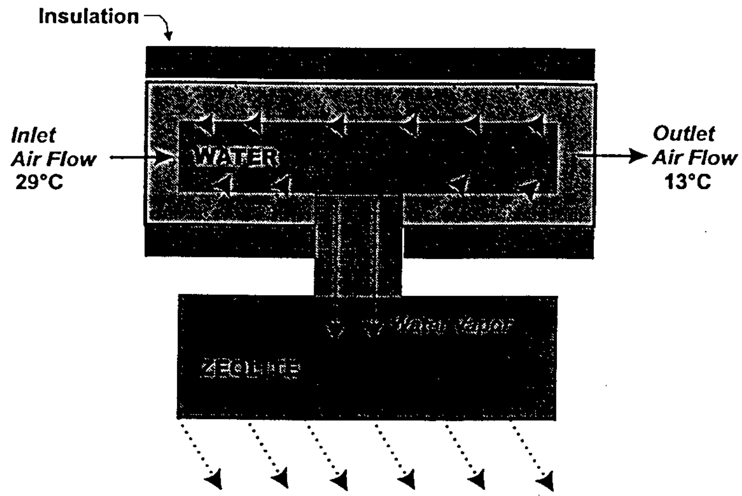

Figure 2. Schematic drawing of the Advanced Personal Air Conditioning System (APACS). Dotted arrows present heat flow pathways. Dashed arrows depict the path of water vapor produced by boiling water in the heat exchanger.

APACS power requirements are minimal because the only externally powered components are the blowers required to cool the zeolite bed and also force the ventilation airstream through the heat exchanger. Most heat exchange within APACS occurs due to physical processes (boiling, adsoption). Liquid cooled systems have high power requirements because the cooling process must extract all the thermal energy removed from the body by the recirculating cooling liquid. APACS has lower energy extraction requirements because it takes advantage of the enthalpy change occurring as the ventilation airstream transits across the body surface. As an open loop, air cooled system, APACS need only lower ventilation air temperature and absolute humidity. For example, a ventilation airstream flowing at 300 L/min and cooled to 25°C and 80% RH is predicted to maintain homeostasis in a light to moderately working 25 year old physically fit male (1).

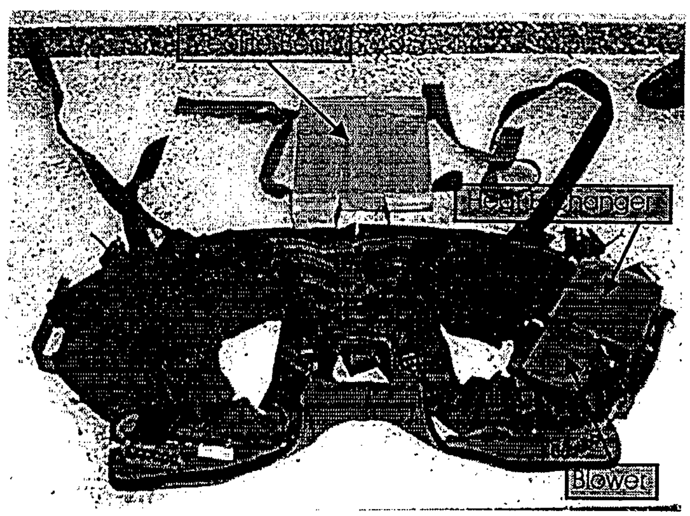

Figure 3. Mockup of the prototype APACS unit mounted on a standard AIRSAFE vest.

These low power requirements allow for compact lightweight cooling system designs. The current prototype APACS configuration, shown in Figure 3, is compatible with the existing AIRSAFE vest and retains all existing survival items. Weight of the APACS (approximately 12-14 lbs.) compares favorably with the weight of the current USN AR-5 head/eye/respiratory protective system (approximately 12 lbs.). In addition, this design will provide active cooling for missions of 3 hours or longer while more advanced designs will permit missions to extend for 24 hours or longer.

Summary: This paper describes the technology behind the development of the USN APACS man mounted cooling system, a key component of HAILSS. APACS represents a lightweight, man mounted cooling system for aircrews requiring no airframe modifications. This system is suitable for all crew stations and can be used during preflight inspections or by non-flying personnel.

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Dr. Kaufman has conducted research in the areas of thermal and respiratory physiology for the U.S. Navy for over 15 years. This work has involved Dr. Kaufman in the development of current protective ensembles used by the U.S. Navy, Air Force, and NASA. He has a Ph.D. in bioengineering from the University of Pennsylvania, a M.S. in biomedical engineering from Drexel University, and a B.Ch.E. in chemical engineering from Cleveland state University.